Magnetically collimated jets with high mass flux

S. Bogovalov[1] and K. Tsinganos[2]

[1]*Astrophysics Institute at the Moscow State Engineering Physics Institute, Moscow 11549, Russia*
[2]*Department of Physics, University of Crete, 710 03 Heraklion, Crete, Greece*

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ABSTRACT
Recent numerical simulations and analytical models of magnetically collimated plasma outflows from a uniformly rotating central gravitating object and/or a Keplerian accretion disk have shown that relatively low mass and magnetic fluxes reside in the produced jet. Observations however indicate that in some cases, as in jets of YSO's, the collimated outflow carries higher fluxes than these simulations predict. A solution to this problem is proposed here by assuming that jets with high mass flux originate in a central source which produces a noncollimated outflow provided that this source is surrounded by a rapidly rotating accretion disk. The relatively faster rotating disk produces a collimated wind which then forces all the enclosed outflow from the central source to be collimated too. This conclusion is confirmed by self-consistent numerical solutions of the full set of the MHD equations.

1 INTRODUCTION

There has been already accumulated enough evidence for a *correlation* bewtween the presence of collimated astrophysical outflows and accretion disks, not only in star formation regions (for a review see e.g., König & Pudritz 2000), but also in other galactic or extragalactic jet-producing sources (for a review see e.g., Livio 1999). For example, in star forming regions, an apparent correlation is found between accretion diagnostics and outflow signatures (Hartigan et al. 1995). Hence, in such cases astrophysical jets are believed to be fed by the material of an accretion disk which surrounds the central object. Most jets are also believed to be powered by the gravitational energy which is released in the accretion process. For example, in the case of jets associated with YSO's it is well known that the observed mechanical luminosity in the bipolar outflows is typically a factor $\sim 10^2$ higher than the total radiant luminosity of the embedded central object (Lada 1985), a fact that seems to rule out radiative acceleration of those jets. Furthermore, the kinetic luminosity of the outflow ($\sim \dot{M}_{\rm wind} v_w^2$) seems to be a fraction ~ 0.1 of the rate at which energy is released by accretion ($\dot{M}_{\rm acc} v_K^2$), if $\dot{M}_{\rm acc} \sim 10 \dot{M}_{\rm wind}$ and the outflow speed is of the order of the Kepler speed v_K. Such a high ejection efficiency is most naturally understood if the jets are driven magnetically (König & Pudritz 2000).

Magnetic fields seem to be also implicated to the most striking feature of jets, e.g., their indeed high degree of collimation. The most dramatic manifestation of such collimation is the HST observed disk/jet system HH30 where the jet appears to be collimated within a cone of opening angle 3° and can be traced to within 30 AU from the star (Burrows et al. 1996). From the theoretical point of view, it has been already demonstrated that the magnetic hoop stress can naturally collimate a plasma outflow (Heyvaerts

& Norman 1989, Bogovalov 1995). In steady-state and axisymmetric analytical models exact solutions of the full set of the MHD equations have been obtained where a wind-type outflow starting either radially from a spherical source or non vertically from a disk becomes eventually cylindrically collimated after crossing the fast critical surface, provided that the source of the outflow is an efficient magnetic rotator (Sauty & Tsinganos 1994, Vlahakis & Tsinganos 1998, Sauty et al. 1999). On the other hand, in time-dependent simulations a similar result has been obtained. For instance, in Bogovalov & Tsinganos (1999, henceforth Paper I), when an initially nonrotating and radial magnetosphere with a uniform radial plasma outflow starts rotating, significant flow collimation is obtained *if* the corotating speed at the Alfvén distance is larger than the initial flow speed.

A serious limitation however of the previous simulations of magnetic collimation is that only a tiny fraction of order $\sim 1\%$ of the mass and magnetic flux of the originally radial wind ends up collimated inside the jet (Paper I). Similarly, in analytical models if the source of the wind is a stellar surface and the disk does not feed the outflow with mass and magnetic flux, very low wind- and jet-mass loss rates ($\dot{M}_{wind}$, $\dot{M}_j$) are obtained. However, in outflows associated with YSO current estimates place $\dot{M}_{\rm jet}$ in the limits $\dot{M}_{\rm jet} \sim 10^{-6} - 10^{-8} M_\odot/yr$ (Ray 1996). And, the inferred from observations mass loss rates of bipolar outflows indicate wind mass loss rates which are also in the range of $\dot{M}_{\rm wind} \sim 10^{-6} - 10^{-8} M_\odot/yr$, depending largely on the luminosity of the YSO's. Therefore, the mass loss rate in the jet has to be a rather large fraction of the mass loss rate in the surrounding wind.

In the present paper we shall show via simulation examples that it is possible to have a large fraction of the wind mass loss rate inside the jet, for suitable distributions of the angular rotation frequency of the system. In the next section

2 we give a detailed comparison of theory and observations regarding fluxes in jets while in section 3 we describe and qualitatively sketch our model and the numerical method to calculate the time-dependent evolution; then, our results are presented for various laws of the distribution of the angular rotation frequency with the magnetic flux function. A summary and physical discussion of these results is given in the last Section 4.

2   MASS FLUX IN JETS: THEORY VS OBSERVATIONS

In this section it is shown how the results of numerical simulations of collimated MHD outflows are inadequate to reproduce the mass flux which observations of some jets seem to indicate.

2.1   Theoretical results

Magnetized winds posses the important property of *selfcollimation*. According to a general analysis, as in Heyverts & Norman (1989), Li et al. (1992), Bogovalov (1995) and analytical examples as in Vlahakis & Tsinganos (1998), at large distances from a rotating central object, the flow of a magnetized wind will be partially collimated into a jet directed along the axis of rotation, *if* there exists a poloidal fieldline which encloses a finite poloidal current. Hence, it is argued that the observed astrophysical jets are collimated by magnetic stresses. Numerical simulations seem to confirm this conclusion. For instance, in simulations performed by the method of relaxation as in Oyued & Pudritz (1997), Ustyugova et al. (2000) Krasnopolsky et al. (2000), Kudoh et al. (1998) and Keppens & Goedbloed (2000), steady state solutions have been obtained in the nearest zone of the simulation with a dimension comparable to the size of the critical surfaces. Nevertheless, although in all those studies collimation of the plasma around the axis of rotation has been found, these results cannot be directly compared with observations of jets.

In observations of jets we deal with scales which are rather large compared with all scales in the nearest zone, such as, the dimension of the accretion disk, the size of the critical surfaces, etc. In the observational scale, the central source would appear simply as a point. Therefore, it is important for a direct comparison with observations to have a solution of the problem at large distances. Up to now, the only self-consistent solution of the problem of the MHD wind structure at large distances from the central object seems to have been obtained in Paper I, where it was found in all analysed cases that a narrow jet is indeed formed over very large distances. However, the mass flux in this jet is only a small fraction of the total mass flux of the originally spherical wind. And, this result appears to be rather general for all cases considered in the analysis. In particular, calculations for a wide class of outflows with *disk-like* laws of rotation and also including winds with a thermal pressure, provided a similar result (Tsinganos & Bogovalov 2000, henceforth Paper II).

To illustrate that this feature of the simulations is independent of the parameters, we present in Fig. 1 the results of calculations on the jet structure in a cold wind from the
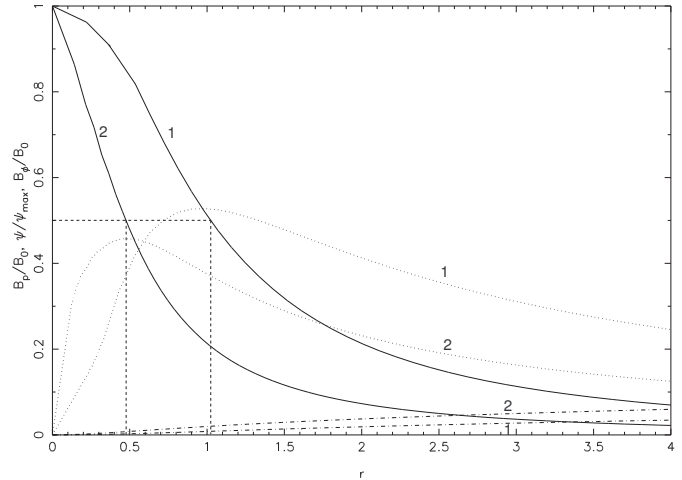

Figure 1. Normalized distributions of poloidal (solid) and toroidal magnetic field (dotted) components together with the relative mass flux (dash-dotted) in a simulated jet as a function of the cylindrical distance r from its axis and for two values of the parameter α in Eq. (1), $\alpha = 1$ in (1) and $\alpha = 2$ in (2)

study of Paper I and for an accretion disk-like law of rotation. The angular velocity in this case decreases with an increase of the magnetic flux, as

$$\Omega = \alpha \frac{v_0}{R_a} \exp(-3\frac{\psi}{\psi_{\max}}), \qquad (1)$$

where ψ is the magnetic flux through a surface of radius r, $\psi_{\max}$ is the total magnetic flux in the upper hemisphere, v_o the constant outflow speed of the initial non rotating star where the Alfvén spherical distance is R_a.

In Fig. 1, the jet structure is shown for two values of the parameter α, $\alpha = 1$ and $\alpha = 2$. The wind consists of two parts. One component is directed along the axis of rotation and represents the jet with mass flux $\dot{M}_{\rm jet}$. The second component expands radially as in ordinary winds. The total outflowing mass flux is concentrated in the wind. Therefore it is natural to define the total mass flux rate as $\dot{M}_{\rm wind}$. In all cases under consideration the mass flux is proportional to the magnetic field flux represented in Fig. 1 by dash-dotted lines. Therefore, the relative mass and magnetic field fluxes are the same. Although the radius of the jet differs significantly, the relative mass flux appears to be the same in the two cases and is of order 1%. This result illustrates our general conclusion that for all sets of parameters examined, we obtain in the jet a tiny fraction of the total mass flux in the wind. The amount of the mass flux in the jet does not depend on the distance from the source in the asymptotic regime considered here, since the other part of the outflow expands radially.

These results are valid for jets spontaneously collimated by magnetic stresses from an initially isotropic wind. An analysis of the results of simulations of outflows from accretion disk-like objects in the nearest zone performed by Ustyugova et al. (2000) and Krasnopolsky et al (2000) provide evidence that in these cases as well we have a small fraction of the mass flux in the jet in comparison with the total mass flux in the wind. For the solution obtained in Ustyugova et al. (2000) this is evident and the authors of

this paper stress that the collimation of their wind is very small, even in the nearest zone.

It is likely that the jet from the wind considered by Krasnopolsky et al. (2000) finally will also carry a small relative mass flux because they considered a wind from a so-called *slow magnetic rotator*. We recall that it has been proposed to classify magnetic rotators ejecting a cold plasma into two groups, slow and fast magnetic rotators, according to the value of the parameter $\alpha = \Omega R_a/V_0$, where R_a is the initial Alfvenic radius of the outflow, V_0 is the initial velocity of the plasma and Ω the angular rotation frequency (Paper I). Actually, this parameter can be also written as $\alpha = 2\pi T_{\text{travel}}/T_{\text{rot}}$, where T_{travel} is the time the plasma spends travelling from the base of the outflow to the Alfvenic surface at a radius R_a and T_{rot} is the period of rotation. For the slow magnetic rotators, $\alpha < 1$ and the plasma leaves the sub Alfvenic region where it can be efficiently accelerated and collimated in a time interval which is small compared to the period of rotation of the central source. That is why winds from slow rotators do not corotate with the ejecting object in the subAlfvenic region (no matter if the ejecting object is a star or an accretion disk). It is exactly this situation that we observe in the solution by Krasnopolsky et al. (2000). It follows from Fig. 3 of this paper that the plasma never corotates in their solution. This means that they consider the outflow of plasma from a slow rotator with $\alpha < 1$. But the collimation of the ejected plasma from slow rotators is not effective and therefore jets with a ratio $\dot{M}_{\text{jet}}/\dot{M}_{\text{wind}} \sim 1\%$ as in Paper I will be produced also.

We conclude that in all available models of magnetized winds, jets with a ratio $\dot{M}_{\text{jet}}/\dot{M}_{\text{wind}}$ not higher than 1% are obtained. It is interesting to compare this value with the corresponding measured value of observed jets from astrophysical objects.

2.2 Observations

Although jets have been observed in association with many astrophysical objects of different scales and nature (Livio 1999), the most reliable information on the mass flux in jets is obtained apparently only for several YSO's (Hartigan et al. 1995). However, even in these objects estimates of the ratio $\dot{M}_{\text{jet}}/\dot{M}_{\text{wind}}$ do not seem to be available in the literature. There only exist estimates of the ratio $\dot{M}_{\text{jet}}/\dot{M}_{\text{accr}}$ where $\dot{M}_{\text{accr}}$ is the accretion rate, for a few YSO's (Hartigan et al. 1995). Early estimates of $\dot{M}_j$ were too low, as they underestimated the neutral fraction in the jet (Raga et al. 1990). More recent calculations suggest that more than 90% of the jet may be neutral (Hartigan et al. 1994, Morse et al. 1995). The luminosity of jets in some forbidden lines, basically O I, indicates mass-loss rates in the interval $10^{-8}-10^{-10}M_{\odot}yr^{-1}$ while the accretion mass rate derived from the infrared luminosity of the disks is in the range of $10^{-6}-10^{-8}M_{\odot}yr^{-1}$. The largest value of the ratio $\dot{M}_{\text{jet}}/\dot{M}_{\text{accr}}$ is about 7% for HH 47 (Hartigan et al. 1994) which demonstrates that at least some YSO's have a ratio $\dot{M}_{\text{jet}}/\dot{M}_{\text{wind}} > 1\%$ since for YSO's $\dot{M}_{\text{wind}} < \dot{M}_{\text{accr}}$ (Pelletier & Pudritz 1992, Ferreira & Pelletier 1995).

Thus, from the above considerations it follows that there seem to be at least some cases of jets where the mass flux in the jet is comparable to the mass flux in the surrounding wind. As a result, the theory of spontaneous magnetic
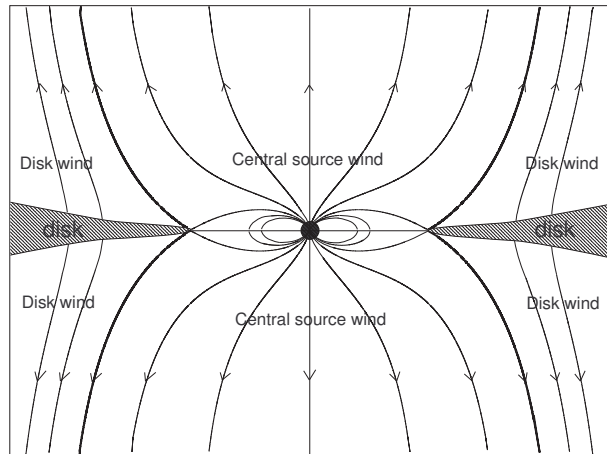

Figure 2. Illustration of the model under consideration. A slowly rotating central source emits a roughly radially expanding at the base outflow which is forced to collimate by the wind from the fast rotating inner edges of the surrounding accretion disk.

collimation of jets should be able to incorporate the possibility to form jets with such high ratio of mass loss in the jet to the mass loss in the wind.

3 JETS WITH HIGH MASS FLUX

In this section we substantiate our model with results of numerical simulations for outflows from a central source collimated by an envelope of rapidly rotating disk-wind.

3.1 Qualitative analysis

The rather dramatic discrepancy of the prediction of the theory of magnetic collimation with the corresponding observations on the ratio of the mass flux in the jet and the wind raises a question on the ability of the mechanism of magnetic collimation to provide the collimation of high mass fluxes into the jets. Qualitatevely the answer to this question follows from an asymptotic theorem formulated in Heyvaerts & Norman (1989), Li et al. (1992) and Bogovalov (1995). According to this theorem, asymptotically, i.e., at large distances from a rotating central source emitting a magnetized outflow, there exists at least one streamline of the wind with $\Omega(\psi) \neq 0$ which is directed exactly along the axis of rotation.

Let us consider the following simple and limiting case. Assume that the source of the jet consists of a Keplerian disk which launches a magnetized wind and a central source emitting from its base an isotropic wind (Fig 2.). Let us also assume for simplicity that the central source does not rotate. Then, the wind from the central nonrotating source is surrounded by the wind from the accretion disk which is in Keplerian rotation. According to the asymptotic theorem, in the wind from the disk there should exist at least one streamline which is collimated exactly along the axis of rotation. But then, automatically all the mass flux enclosed by this streamline will be collimated too. It is important to note that in this case there is no physical limitation on the amount of collimated mass flux. All mass from the central

nonrotating part of the outflow is expected to be collimated in a jet.

The slow rotation of the central part of the source of the wind is apparently not the only way to increase the amount of the mass flux in the jet. Let us have a look on the problem from another point of view. The collimation of the plasma is controlled by the Lorentz force which acts accross the field lines. Using a local coordinate system with unit vectors $(\hat{p}, \hat{\varphi}, \hat{n})$ where $\hat{p}$ is tangent to the poloidal field line and $\hat{n}$ is directed towards the local centre of curvature of the poloidal line, the Lorentz force along $\hat{n}$ is,

$$F_n = \frac{J_p B_\varphi - J_\varphi B_p}{c}. \tag{2}$$

The first term in this expression represents the collimating force produced by the toroidal magnetic field B_φ. The second term corresponds to the decollimating force from the poloidal magnetic field. The collimating Lorentz force is as follows

$$F_n = \frac{1}{4r} \frac{B_p \partial (rB_\varphi)^2}{\partial \psi}. \tag{3}$$

where $d\psi = 2\pi r B_p dl$, r - is the distance to the axis of rotation, B_p is the poloidal magnetic field, dl is the length element across the magnetic field. The toroidal magnetic field can be estimated from the frozen in condition as

$$B_\varphi \approx \frac{r\Omega B_p}{v_p}. \tag{4}$$

provided that we consider the flow far enough from the Alfvenic surface, and, therefore, we can neglect the toroidal velocity of the plasma in comparison to the poloidal velocity. This is a good approximation for analytical solutions with radial poloidal streamlines (Tsinganos et al. 1992, Figs. 2,3) and also in numerical simulations as in Krasnopolsky et al. (2000, Fig. 3) and Ustyugova et al. (2000, Fig. 10). Let us introduce the following definition

$$\mu = (r^2 \Omega B_p / v_p) \tag{5}$$

It follows from (3) that the derivative $\partial \mu^2/\partial \psi$ defines the collimating force. If $\partial \mu^2/\partial \psi > 0$ the Lorentz force is directed towards the axis of rotation. The plasma in these regions is collimated. Otherwise the plasma is decollimated. In general, both such regions can exist in magnetized winds (see for example Fig. 10 in Paper I). A similar effect of partial decollimation of the wind has been found in Beskin & Okamoto (2000) and also Ustyugova et al. (2000). It follows from the previous asymptotic theorem that if $\mu \approx 0$ in the central part of the flow while it increases outwards, then all this part of the flow will be collimated. A strong decrease of this parameter in the central part of the outflow can be achieved also if the poloidal magnetic field is close to zero in the central part of the flow or the velocity is drastically increased. It seems reasonable to assume that the efficiency of the collimation would be increased in these cases as well.

All these assumptions need to be carefully verified. In this paper we verify only the prediction of the asymptotic theorem that arbitrary large flux of plasma and magnetic field can be collimated into the jet provided that the angular velocity in the central part of the flow is negligible.

3.2 Model

To verify the above conclusion that with a zero rotational velocity in the central part of the flow the mass loss in the jet can be remarkably increased if it is surrounded by a rotating envelope, we use the simplest model wherein we have a cold wind outflow from a spherical source. The initial magnetic field is taken to be that of a split-monopole. The details of this model are described in Paper I. The justification why such a model can be applied for investigating the general properties of magnetic collimation in a wide class of outflows is given in Paper II. In Papers I, II, the solution of the problem of the selfconsistent steady state plasma outflow was divided in two stages. At the first stage the problem was solved in the nearest zone by numerically simulating the time dependent plasma outflow. When the initial flow relaxed to a final steady state outflow, this solution was used for obtaining a steady state outflow in the far zone.

3.3 Results

According to our previous qualitative analysis, it is expected that the fraction of the mass collimated into the jet will be increased in comparison to the case of a constant or accretion disk-like rotation, if the angular frequency function $\Omega(\psi)$ is negligible in the central parts of the flow. To verify this conclusion, we calculated the steady state of an outflow from a differentially rotating object wherein the angular velocity increases with the magnetic flux ψ. In Fig. 3 the poloidal lines of the flow are plotted in the nearest zone of the central object which rotates according to the following law

$$\Omega(\psi) = \begin{cases} 4.5 \times \dfrac{\xi}{7[50(\xi-0.7)^2+0.1]} \dfrac{v_0}{R_f} & : \quad \xi < 0.7, \\ \\ 4.5 \dfrac{v_0}{R_f} & : \quad \xi \geq 0.7, \end{cases} \tag{6}$$

where $\xi = \psi/\psi_{max}$. According to this law basically only the part of the source near the equator rotates while near the axis there is practically no rotation. The thick lines show the location of the Alfvén and fast mode critical surfaces. They are splitted only at the equatorial region since only in this region a toroidal magnetic field is generated. It follows from this figure that as the rotation of the outer part of the central source is fast enough, the collimation of the flow from the central part occurs already in the nearest zone of the flow.

Fig. 4 shows the flow in the far zone. In this zone the collimation continues in a logarithmic scale as it was discussed in Paper I. In addition however, now we have the formation of a shock wave in the collimated flow.

The internal parts of the wind are not collimated by the Lorentz force since this layer of the outflow originates in a practically nonrotating central source. However, this wind is indirectly collimated by the outer layer of the outflow. This part of the wind affects the supersonic flow coming from the central part similarly to a curved wall in the flow of a supersonic gas (Landau & Lifshitz 1975, p. 429). The shock is formed where the characteristics intersect. The beginning of the shock and its position in the flow are shown schematically in Fig. 4 by a thick solid line. The process of the formation of the shock front can be better seen in Fig.
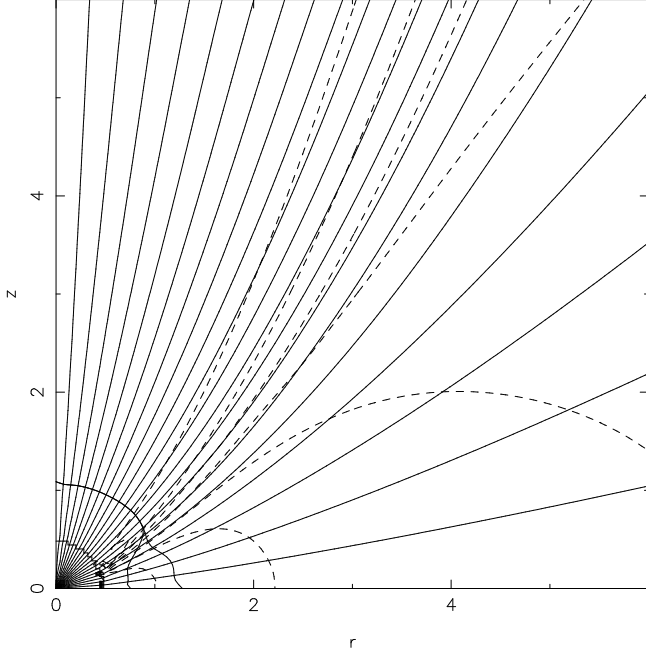
Figure 3. Poloidal lines of isotropic at the base wind from a differentially rotating object, wherein rotation is basically concentrated at the equatorial region. The star is located at the lower left corner of the figure. Solid lines denote poloidal magnetic field lines placed at equal angular distance from each other at the isotropic outflow and dashed lines poloidal electric currents generating the toroidal magnetic field. Thick solid lines surrounding the star indicate Alfvenic and fast mode surfaces and split close to equator because basically only there a toroidal magnetic field is generated.

Figure 4. Poloidal lines of magnetic field of a differentially rotating wind as in previous figure but in the far zone. In contrast to previous figure, the magnetic flux enclosed by each field line differs by a constant value from line to line. Thick solid line marks the beginning and assumed position of a shock wave.

Figure 5. Distribution of magnetic field across the flow in a plane located at various labeled distances z across the rotation axis. The magnetic field is normalized to its value at axis. Sequence of curves shows the formation of a harp front in the distribution of the magnetic field which finally leads to the formation of a steady state shock wave in the flow at $z > 143$. Dotted line denotes normalized toroidal magnetic field for the largest z and dashed-dotted line the relative mass flux for the same distance z. The jet contains more than 50% of the initial total mass flux.

5, where the distribution of the normalized poloidal magnetic field *vs.* distance to the axis of rotation is shown for different heights z from the central source. The poloidal magnetic field is raked by the toroidal magnetic field generated in the outer parts of the wind. But the central parts near the axis still do not have received the signal about this raking. Therefore a wave-like structure of the poloidal magnetic field is formed, as in Fig. 5. The numbers near the curves show the distance z expressed in units of the initial Alfven radius. It is clearly seen that the shape of this wave-like structure of the poloidal magnetic field line changes with z. The front of the wave becomes more sharp with increasing z. Finally, the front becomes practically vertical forming a shock. Unfortunately, the flow containing this shock cannot be calculated with our code, since we solve the steady state Cauchy problem in the two dimensional space of r,z (Paper I).

For the last z and just before the shock is formed, we also plot in this figure the dependence of the normalized toroidal magnetic field and the normalized poloidal magnetic field flux. It can be seen from this figure that at the maximum of the toroidal magnetic field which corresponds to the boundary of the jet which will be finally formed after the passage of the shock front from the flow, the collimated flux exceeds 50% of the total initial flux. For comparison, for jets from sources with uniform or disk-like rotation laws (Paper I), we had at maximum about 1% of the flux collimated.
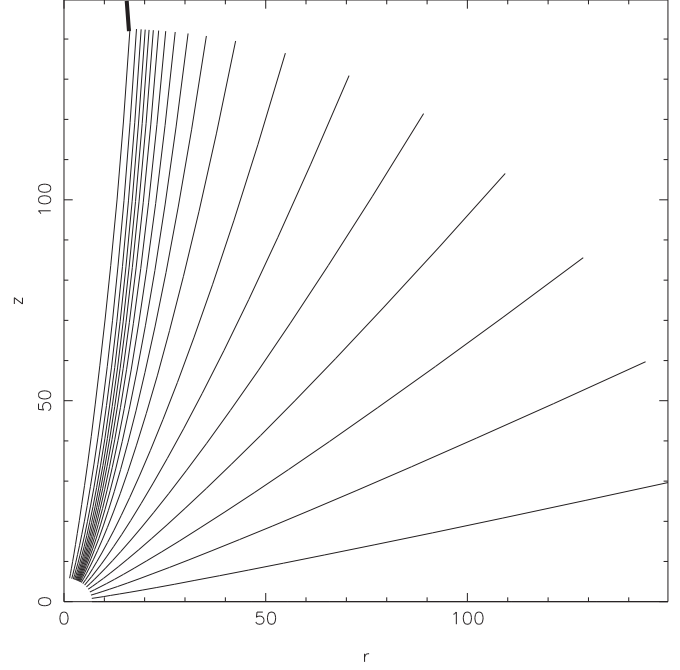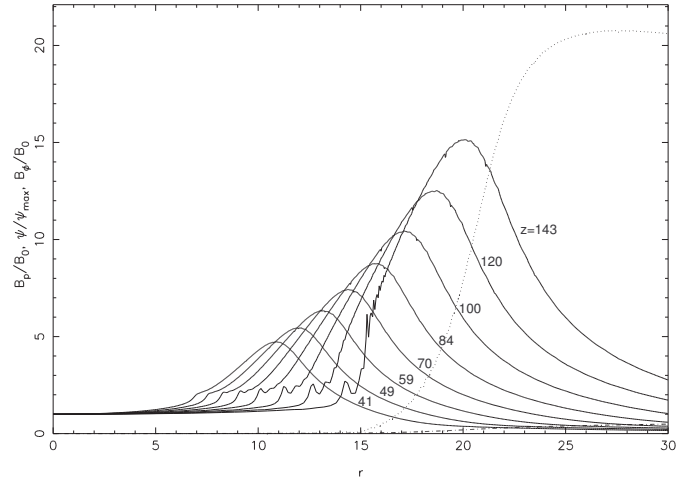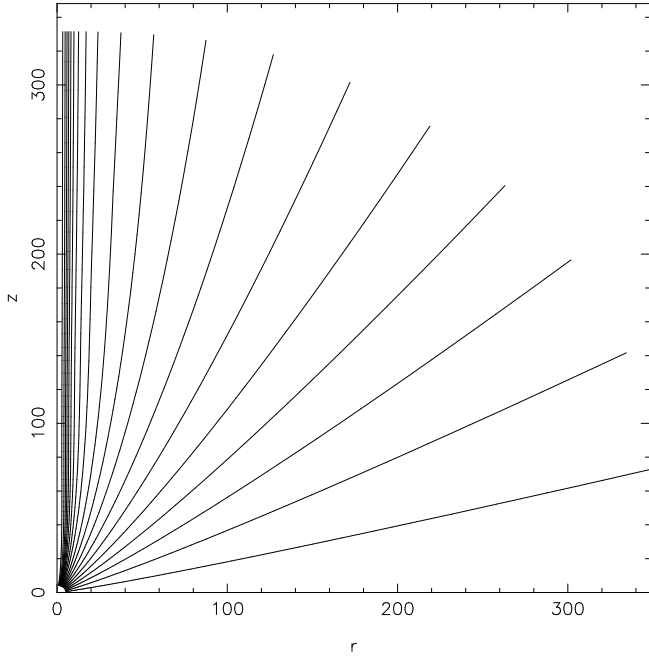
Figure 6. Poloidal lines of the flow in the far zone of the wind from an object rotating with the law given by Eq. (7). The flux difference between the field lines is constant. A shock wave is not formed in this case.

Figure 7. Distribution of the normalized poloidal (solid line) and toroidal magnetic field in the jet formed by the differentially rotating source, as in Eq. (7). The jet formed in this model has a rather uniform inner structure.

The formation of the shock front in the collimated wind occurs only if the characteristics of one family begin to cross at some point (Landau & Lifshitz 1975). But this crossing does not happen in every flow. If the central part of the flow is compressed by the outer part of the wind close enough to the central source the shock wave is not formed. For example, with th efollowing form of the angular velocity distribution,

$$\Omega = 3.5\xi^2 \frac{v_0}{R_f} \,, \tag{7}$$

the shock wave is not formed. The flow from this source in the far zone is shown in Fig 6. The jet from this source indeed is similar to observed astrophysical jets. The corresponding to Fig. 5 distribution of physical quantities with distance from the jet axis in this case is shown in Fig. 7. The jet has a structure which remarkably differs from the structure of the jets from the uniformly or disk-like rotating objects discussed in Paper I (see Fig. 1). Thus, the jet under consideration has uniform poloidal magnetic field and in this specific case contains also a remarkable part ($\sim 25\%$) of the total magnetic and mass flux.

4   SUMMARY AND DISCUSSION

According to recent studies on the spontaneous magnetic collimation of MHD winds, the flow of plasma at large distances from the source consists of a jet and a radially expanding wind (Paper I). The density of the plasma in the wind drops down with distance while the jet is mixed with the surrounding circumstellar medium over a distance small compared to its length. Since the density of the plasma in the distance of the terminating shock is rather small, this
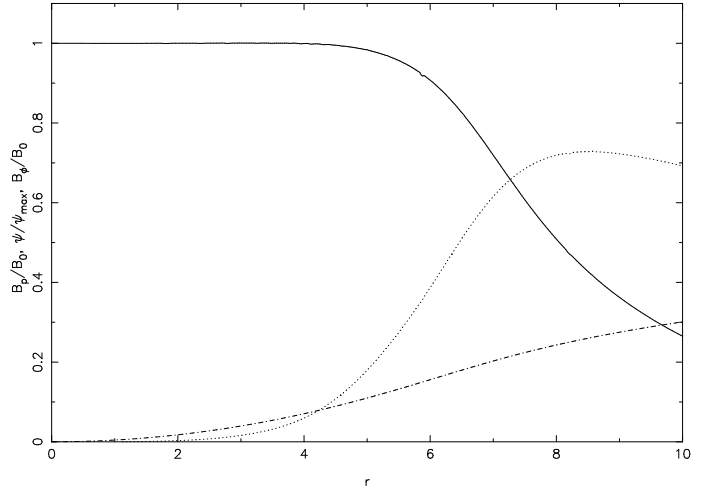
process is hard to be observed directly. Therefore for an estimate of the mass flux ratio $\dot{M}_{\rm jet}/\dot{M}_{\rm wind}$ we use indirect methods estimating the ratio $\dot{M}_{\rm jet}/\dot{M}_{\rm accr}$. A comparison of the observable characteristics of jets from some YSO's provides evidence that the mass loss rate in the jets of these objects is a remarkable fraction of their total mass loss; this observed high mass loss ratio in jets greatly exceeds the prediction of the simplest models. However, these observational data can be explained if we assume that the characteristics of the source of the wind in the central part of the outflow differ remarkably from the characteristics of the surrounding wind. In principle, an arbitrary large fraction of the wind can be indirectly collimated into a jet when the central part of the source does not rotate significantly and it is surrounded by a rapidly rotating envelope. Our numerical simulations totally confirm this conclusion, leading in some cases to a collimation of up to 50% of the flux of the wind into the jet.

The idea that a jet with a relative high mass loss fraction should be launched from the central parts of a source which produces an outflow with properties strongly different from those of the surrounding wind, actually is not new. Several studies have led to the same conclusion, albeit from different perspectives. For instance, the extraction of the rotational energy of a central black hole by a magnetic field and its eventual conversion to Poynting flux and relativistic $e^+ - e^-$ pairs in the Blandfrod & Znajek (1977) mechanism, is now a rather key element in models of AGN's (Sol et al. 1989, Pelletier et al 1996). Also, the idea that the observed jets are the result of the interaction of a central star with an accretion disk was proposed in the context of young stellar objects by Shu et al. (1991).

What conditions can actually be realized in the central parts of a wind to produce jets with a high mass outflow? Our analysis has shown that the slow rotation of the central part of the source of the wind is not the only way to increase the fraction of the mass lost in the jet. Apparently the same effect can be obtained by decreasing the poloidal magnetic field in the central part, or by strongly increasing the plasma

velocity. These are possibilities which should be investigated in more detail.

First, it is unlikely that the magnetic field in the central parts of the source is decreased remarkably. Most models on plasma ejection from accretion disks predict the opposite tendency : the poloidal magnetic field is rather enhanced at the central parts of the source (Oyued & Pudritz 1997, Ustyugova et al. 2000, Krasnopolsky et al. 2000). Therefore we are left with the following possibilities: either the central angular velocity of rotation is decreased, or, the velocity of the plasma in the central parts of the source is increased. Of course a combination of these two conditions is also possible.

The idea that the source of the jet rotates rather slowly may be quite reasonable, at least in relation to YSO's. It is evident that a protostar should rotate more slowly than the inner edges of its Keplerian accretion disk and observations indeed confirm this prediction. We do not intend to argue here that the matter in the jet is ejected from the protostar. The close disk-jet connection shows that the matter in the jet is supplied by the accretion disk (Livio 1999). But it is reasonable to assume that this matter penetrates in the magnetic field of the central star, partially falls down on the surface of the star and partially is ejected outwards (Shu et al. 1991). In this case only the magnetic field of the jet is connected with the central star. Schematically this picture of the outflow is presented in Fig. 2. According to this scheme the disk not only supplies the plasma of the jet, but also it produces the magnetized wind which collimates the outflow from the central source into a jet.

Another possible configuration for the formation of jets with relative high mass outflow is connected to the possibility of an outflow from the central source with speeds much higher than those of the surrounding wind (see also Paper II). It is important to note that this mechanism allows naturally the collimation of a relativistic plasma. In Paper I it was shown that a relativistic plasma is practically not collimated by the magnetic

stresses even at very fast rotation (see also, Bogovalov 1997, Bogovalov 2000). This is a rather intrinsic property of relativistic outflows.

There are two reasons why a relativistic plasma cannot be selfcollimated. In a relativistic outflow the role of the electric field becomes important. According to the frozen in condition, the electric field is $\mathbf{E} = -\mathbf{v} \times \mathbf{B}/c$. In the nonrelativistic limit this electric field is negligibly small and therefore the Coulomb force on the induced in the plasma electric charge is also negligible. In the relativistic limit the situation changes. The Coulomb force becomes comparable to the Lorentz force but it affects the plasma in the opposite direction (Bogovalov 2000), drastically decreasing the effect of the magnetic collimation. The collimating force increases with the angular velocity of the rotation of the central source. However, even at very fast rotation rates the collimation remains very inefficient since another relativistic effect comes into play. The effect of collimation depends not only on the force pushing the plasma to the axis of rotation, but also on the mass of the plasma. In the relativistic limit the flux of the energy of the electromagnetic field at fast rotation exceeds the flux of the energy of the matter. But according to the relativistic relationship between energy and mass, the flux of the energy is equivalent to the flux of matter. The effective mass of the outflowing relativistic plasma is effectively

increased by the contribution of the mass of the electromagnetic field. Therefore the increase of the angular velocity of the rotation or the magnetic field does not provide a more efficient collimation of the relativistic plasma. The effective mass of the plasma increases almost proportionally to the collimating force.

In the proposed scenario, which may be applicable for example to blazars, the relativistic plasma is ejected from a central source, for example a black hole, e.g., via the Blandford & Znajek (1977) mechanism. Then, the collimation of this plasma is provided by the magnetic nonrelativistic wind from the accretion disk, as shown in Fig. 2. A more detailed verification of this mechanism for the collimation of relativistic plasmas will be presented in another connection.

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